

The Goddard High Resolution Spectrograph

David R. Soderblom and Lisa E. Sherbert

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore MD 21218

Abstract. The Goddard High Resolution Spectrograph (GHRS) was on *HST* at the time of its launch in 1990, and was withdrawn from *HST* during the second servicing mission in 1997. This paper summarizes key events during the operational history of the GHRS and provides a recapitulation of results from the many calibrations that have been done.

1. Introduction

This paper will provide a brief look at the state of calibrations for the GHRS. By the time the present volume appears, a new version of the *HST Data Handbook* will have been completed, and that volume has all the details that are only referenced here. Before we begin, we wish to emphasize two important statements: First, for up-to-date information, you should go to the GHRS web page, under the STScI home page. Second, if you select GHRS observations from the *HST* Data Archive, always recalibrate them to ensure you are using the best possible calibration reference files.

The GHRS was a spectrograph built to address a number of scientific goals through ultraviolet spectroscopy. Two detectors were used, one for far-UV work and one for near-UV. “Side 1” incorporated a detector optimized for the far ultraviolet, having a faceplate of CeI with a LiF window. This made Side 1 blind to photons above about 1800 Å but sensitive down to almost 1100 Å.

Side 1 included a low-resolution mode for faint objects, realized with grating G140L, with a resolving power $R = 2,000$. This mode was more sensitive than the FOS at many far-UV wavelengths and had less background as well. Medium resolution capabilities ($R = 20,000$) were provided with grating G140M. High resolution ($R = 80,000$) was achieved with Echelle-A.

“Side 2” worked in the near-UV, and had a faceplate of CeTe on a MgF window. This made it sensitive down to Lyman- α , and it was best from about 1700 to 3300 Å. Side 2 was also solar-blind, and had three medium-resolution gratings ($R = 20,000$): G160M, G200M, G270M, as well as a high resolution mode ($R = 80,000$) with Echelle-B.

1.1. Instrument Operation

The GHRS had two entrance apertures for celestial targets. The Large Science Aperture (LSA) was 2 arcsec square (1.74 arcsec square after COSTAR), and was designed to get good fluxes. The LSA mapped onto 8 diodes of the Digicon in width, and one in height, and it passed 95% of light post-COSTAR.

The Small Science Aperture (SSA) was intended for getting good wavelengths, and it was 0.25 arcsec square (0.22 after COSTAR), and it mapped onto one diode. The SSA had 50 to 60% of throughput of the LSA (post-COSTAR), depending on wavelength and the quality of the centering of a star.

There were also two wavelength calibration lamps (SC1 and SC2), and they had their own apertures.

A typical observing procedure was:

1. DEFCAL: to find the aperture
2. Acquire target into LSA: find the object
3. Acquisition IMAGE (optional): where was the object?
4. Move to SSA and peak-up if that aperture was used.
5. SPYBAL: SPectrum Y BALance to center spectrum in the cross-dispersion direction.
6. Wavelength calibration exposure (optional).
7. One or more ACCUMs.
8. RAPID mode for time-resolved spectra.

Some items were optional steps, while the other steps were usually present. The types of data produced and their structures are described in the Data Handbook (DH). DEFCALs and SPYBALs were calibrations internal to the GHRs. SPYBALs are especially useful to an archival researcher as a means of improving the default wavelength calibration (see below).

1.2. Key Events During the Life of the GHRs:

1. Most important of all was the launch inside HST in April, 1990!
2. The Side 1 low-voltage power supply (LVPS) had repeated problems in the summer of 1991, eliminating access to both low- and high-dispersion modes in the far-UV (G140L and Ech-A). Prior to this loss, Ech-A was the most-requested GHRs grating, but deconvolution techniques were developed that allowed G160M (Side 2) observations to approach Ech-A resolution. Some of this science was done with Side 2 during Cycles 2 and 3.
3. The LVPS problem was fixed during SM1, restoring important capabilities and leading to greater GHRs usage.
4. The failure of lamp SC1 eliminated redundancy for wavelength calibration, also in 1991. Fortunately, the specifications for the lamps were very conservative and SC2 had ample lifetime to meet observer needs.
5. Acquisitions during the early years had to specify BRIGHT and FAINT limits, leading to failed ACQs and wasted telescope time. The implementation of BRIGHT=RETURN eliminated this problem. Also, BRIGHT=RETURN used 32 bits, preventing register overflow, which had been a problem with very bright stars.
6. Other flight software changes were made to improve acquisitions and overall operation.
7. The installation of COSTAR during SM1 changed the net throughput of the LSA very little (two extra reflections offset the better PSF), but the contrast of the PSF changed enormously, resulting in reliable fluxes. SSA throughput improved too, by about a factor of two.
8. Prior to COSTAR, *HST*'s spherical aberration was sometimes a "feature" for acquisitions in that the algorithm could find the wings of the PSF even when the initial centering was poor.
9. A major failure occurred one week before SM2, resulting in the complete shutdown of the GHRs. The most important loss was some special observations that were to be made with the COSTAR mirrors withdrawn to try to determine the origin of far-UV sensitivity losses.

2. GHRs Calibration Results

The dimensions of a GHRs spectrum include:

- Flux, with several components of uncertainty on different wavelength scales:
 - Overall spectrum level (scale $\sim 100 \text{ \AA}$).
 - Shape of the spectrum (scale $\sim 50 - 100 \text{ \AA}$).
 - Noise and structure in spectra (scale ~ 1 diode).
- Wavelength, both in zero-point and scale (dispersion).
- Position and imaging quality (acquisition, PSF, LSF).
- Timing (start, stop, interrupts, doppler compensation and correction).
- Other (instrument and spacecraft errors).

2.1. About Fluxes and Flux Calibrations

The flux calibration is established by observing a standard star and then comparing the observations to a reference spectrum, which is taken to represent “truth.” The result is the sensitivity function, in (flux units) per (count rate) at a given wavelength.

The first major problem is that the response of the instrument depends of the position of the spectrum on the photocathode. Also, structure in the spectrum of the standard star makes analysis more difficult and partly resolution-dependent.

“Sensitivity” describes the overall response function, while “vignetting” refers to effects that depend on position on the detector. The components of the “flux” calibration (everything that goes into determining the vertical scale of the spectrum) include:

1. Spectrum level:
 - The sensitivity function for the grating + detector.
2. Spectrum shape:
 - The vignetting function, to correct for photocathode position.
 - The echelle blaze function, for the echelle gratings only.
3. Level and shape:
 - Time-dependent corrections to sensitivity functions.
4. Noise and structure (“flatfields”)
 - Granularity function, available only for G140L.
 - Granularity determination, accomplished with FP-SPLITS or other means.
 - Corrections for bad diodes.
 - Corrections for diode-to-diode response.

2.2. Flux I: Spectrum Level and the Sensitivity Function

“Sensitivity” and “vignetting” are intertwined, and at some level the distinction is arbitrary. That distinction is made by defining the vignetting function at the center of a spectrum to be 1.

Some issues of determining sensitivity can be seen by comparing the observed spectrum of a standard star to its reference spectrum (see the DH). To separate sensitivity from vignetting, a series of spectra are obtained spaced by half the bandwidth, so each wavelength is observed twice. The calculation is iterated to convergence.

The presence of major spectrum features – especially Lyman- α – is a major problem, exacerbated by these being astrophysically important wavelengths. Also, the observed spectrum below 1140 Å has few counts and much curvature, making the fitting difficult. (At any rate we had no reference spectrum defined below 1140 Å anyway.)

Recent work in this area includes:

1. ISR085 on G140L sensitivity and vignetting. The G140L sensitivity file installed post-COSTAR was shown to be wrong, probably because of incorrect allowance for the new white dwarf flux scale. The correct calibration reference files are now in CDBS and the time-dependent sensitivity is provided for in CDBS.
2. ISR088 on redetermining sensitivity for G140M and Echelle-A. The problems are similar to those for G140L.
3. ISR089, on time-dependent sensitivity for Side 2 first-order gratings and ISR090, a check on Ech-B sensitivity.

2.3. Flux II: Sensitivity Monitoring and Time-Dependent Effects

Sensitivity monitoring of the GHRIS was done separately for Side 1 and Side 2. For the Side 2 observations, gratings G160M (centered at 1200 and 1500 Å), G200M (2000 Å), and G270M (2500 and 3000 Å). This sequence was repeated approximately every three months.

Pre-COSTAR Prior to the installation of the COSTAR mirrors, the GHRIS LSA had the same overall absolute throughput as post-COSTAR, but the blurred PSF put significant power into the wings. The result was that the quality of flux measurements was very sensitive to the centering of the star in the LSA.

Pre-COSTAR observations (ISR036, ISR038) showed excellent reproducibility of count rates for acquisitions and spectra of standard stars, consistent with no change in sensitivity. (Several different stars were observed, primarily BD+28D4211 and μ Col.)

ISR042 confirmed that no changes were seen for the pre-COSTAR GHRIS (Side 2), even below 1200 Å. ISR051 showed that Side 2 pre-COSTAR was stable to within better than 3.6%, consistent with effects of focus and centering.

Post-COSTAR The Side 1 post-COSTAR monitor contained a series of visits of the UV standard BD+28D4211, done with an identical instrumental configuration each time, except that exposure times were increased at later dates to achieve better signal to noise. Grating G140L was used at two wavelengths: 1200 and 1500 Å.

After the Servicing Mission, we could see distinct declines in sensitivity with time, especially on Side 1 below Lyman- α . This was suspected to be due to contamination on the COSTAR mirrors, and a special measurement was planned for just before the second Servicing Mission to verify this. Unfortunately, the GHRIS experienced a catastrophic failure one week before SM2 so these measurements were not done.

Declines in the post-COSTAR sensitivity of the GHRIS are now well-characterized, and provision has been made by providing calibration reference files that apply to specific time periods. These time periods are three months in length, which is short enough that

significant changes did not occur on shorter time scales. This is described in detail in the DH.

Time-dependent effects may be slightly different at different wavelengths. We have ignored this because we have inadequate information to fully characterize it.

Short Time-Scale Effects: Decreasing Counts During an Orbit A series of short-exposures of a star showed a regular decline of observed counts of $\sim 10\%$ over each orbit for a star observed in SSA. This was described in ISR073, together with some possible explanations. Our best hypothesis is that this phenomenon is due to telescope “breathing.” This effect can contribute to flux uncertainty, obviously. However, similar observations through LSA appear unaffected.

Single FGS observations in SSA have shown a similar effect, due to drift of the object out of the aperture.

2.4. Flux III: Other Flux Scale Effects

Flux Correction for Extended Sources `calhrs` assumes that a point source has been observed when reduction to flux is made. If an extended source has been observed, then the flux calibration from `calhrs` will be inappropriate.

To obtain an estimate of specific intensity, multiply the post-COSTAR observed flux by 0.95 ± 0.02 for observations taken through the LSA, and divide by the area of the aperture in square arcsec. This assumes the extended source completely and evenly fills aperture. For pre-COSTAR observations, the correction factor is 0.725 (ISR061).

Correction for Background Counts The background level, or dark current, for both GHRS detectors was very low: about 0.01 counts per second per diode when well away from the South Atlantic Anomaly (SAA). However, for very faint objects the dark level could dominate the signal, and accurate correction for the background is vital.

Because of this, some provision was made in the GHRS commanding software for features that would allow for lower net noise rates compared to standard observing modes. One of these modes used the CENSOR option (ISR045), and the other used a parameter called FLYLIM (ISR054). These are described in previous workshops.

For archival data, there are several options for correcting for the background. ISR070 discusses measurements of the background for Side 2 in detail, and ISR085 describes a model used for estimating background counts, recently implemented. This uses accumulated flight experience to estimate dark counts and works especially well for short exposures.

Results from dark noise calibrations are presented in ISR041 and ISR070. These have been very consistent over instrument lifetime.

2.5. Flux IV: Spectrum shape

Shape Effects from the Sensitivity Function: G140L For most GHRS observations, the bandpass samples only a small portion of the spectrum produced by the grating. Undulations in the sensitivity function, which have length scales of ~ 100 Ångstroms, at most have a small linear effect across a spectrum.

G140L is the exception to this rule because it produces spectra nearly 300 Å long. Therefore spectra from grating G140L may have modest shape effects that have their origin in the sensitivity function. These can be especially pernicious near Lyman- α because the breadth of that feature in the standard stars we observed prevented a good determination of the shape of the underlying sensitivity function at those wavelengths.

Time-dependent sensitivity functions help mitigate this, but this leaves residual uncertainty of $\sim 2\%$ in flux at one wavelength relative to another wavelength more than 50 to 100 Å away in same spectrum, and $\sim 4\%$ in the worst case. These shape effects are probably due to comparing BD+28 to μ Col, and the fact that μ Col is a secondary standard.

Intercomparisons of different stars used as standards often show systematic effects at the $\sim 2\%$ level (R. Bohlin).

Light Falling Off the Diode Array Temperature changes during an observation caused spectrum to move on the photocathode, so the GHRs used SPYBALs to properly center the spectrum on the diode array. A SPYBAL was performed every time a new spectrum element was used (i.e., the first use of a different grating), and approximately every two orbits thereafter. (Sometimes SPYBALs were suppressed to avoid carousel movement.)

This centering can be important because a given spectrum is tilted across the diode array, and a lack of proper centering could result in the ends of the spectrum falling off the array. Again, this is routinely corrected for, and only becomes a problem if SPYBALs were suppressed for long exposures (i.e., for several orbits).

The worst case is for an extended object uniformly filling the LSA. In this case, the width of the spectrum cannot be ignored. The width is equal to the size of the aperture, or about 64 deflection units. For the case of a G140L observation of an extended object in the LSA, we start out with a loss of light. The spectrum is already falling off the array with the ends experiencing about 30% light loss. In the time it takes to drift 25 deflection units, some part or all of the spectrum may fall off the array, resulting in a significant reduction in signal. This effect produces an apparent drop-off in flux at ends of spectrum, similar in form to vignetting.

G270M Vignetting Errors The pre-COSTAR sensitivity calibration used in the pipeline processing between 1991 Nov 11 and 1994 Apr 14 was wrong shortward of 2300 Å for grating G270M. The pre-COSTAR vignetting correction for G270M was inadequate shortward of 2300 Å, and the post-COSTAR vignetting correction shortward of about 2150 Å was not handled properly by **calhrs** because the y -deflection not been measured below 2300 Å. The program which was to correct this failed, and the issue was judged to be not important enough to warrant further work. This is documented in ISR077.

The Echelle Blaze Function The echelle blaze function relates relative fluxes to those observed at the center of a given spectrum order. This function was determined by observing μ Col at different wavelengths in different orders, and then relating those observations to others made with first-order gratings. It is impossible to cover fully a free spectral range or to sample every echelle order, so the blaze function is meant to be a reasonable approximation to the true function. An underlying, but unstated, assumption is that observers used the echelles to measure the strengths or positions of weak spectrum features and were therefore not primarily concerned about the absolute flux level in the final, reduced spectrum.

Inappropriate Background Subtraction In some cases the shape of a spectrum can be distorted if the background is improperly calculated and subtracted. This was seen in the first couple of years of GHRs operation because the background subtraction software fitted a polynomial to the background before subtracting it from the source spectrum. This was done to preserve shape in the background spectrum, but often the background had very few counts so that the fit was spurious. Modification of the procedure to fit to a single value removed the problem.

2.6. Flux V: Spectrum Noise and Structure

The first-order diode-to-diode response variations are removed in **calhrs**. These are independent of the grating, wavelength, etc.

Granularity There are also granularity effects produced in the photocathode faceplates of the detectors. No calibration provided for these because the scope of the task of determining them is impractical. However, grating G140L has been so characterized because its bandpass

is large (see ISR076 for details on how this was derived). For the other gratings, FP-SPLIT was provided to allow for improved signal to noise in the final spectrum.

Dead or Noisy Diodes Each diode was independently monitored. Diodes could exhibit anomalous behavior or fail. These diodes are grouped together into the “Dead or Noisy Diode” category. Use of the COMB parameter helped to work around these. Diodes that showed anomalous behavior over an extended time were turned off for science observations. In practice, the threshold voltage was set to a high value so that it did not detect electrons from the photocathode. The GHRS calibration software corrects for known anomalous diodes.

Spikes Large spikes and unrealistic flux levels were found in a subset of Fall 1995 calibrated GHRS data. The affected observations were all made using the Ech-A grating in orders 35 and 36. Fortunately, this problem only affected a handful of observations in a few proposals. The PIs of the affected programs were notified of the problem, and, in any case, recalibration of the observations solves the problem.

Blemishes Scratches, pits, and other microscopic imperfections in the detector window and on the photocathode surface are “blemishes.” The magnitude of these blemishes depended on how the spectrum illuminated the photocathode near a blemish. Many blemishes have spatial structures and depths that make them difficult to distinguish from real stellar or interstellar features. Therefore, it is difficult to automatically correct data for the effect of blemishes.

In the absence of independent information, individual subexposures can be displayed in diode space to identify non-real spectrum features. The calibration code does not correct for blemishes, but the data quality file (.cqh) contains DQ values marking which pixels are affected by known blemishes. The use of FP-SPLITS aided in blemish removal.

Flaky Diodes These were seen in some Side 2 CVZ RAPID-mode observations. They were attributed to increases in the pre-amp temperature, producing non-linear amplification of input from diodes. They were also seen in some non-CVZ observations, but were not seen on Side 1.

2.7. Flux VI: Summary

The quality of the flux calibration depends on the question asked:

- For absolute flux of a given observation, the work of Bohlin et al. shows internal consistency of 2%, agreement with ground-based to 3%, and systematic external errors less than 15%.
- For the pre-COSTAR instrument, there is no evidence for time-dependent sensitivity changes, but the intrinsic uncertainty of relative fluxes is fairly large due to PSF effects and centering: $\sim 4\%$. This increases with time after initial acquisition of an individual object.
- Post-COSTAR, if same star is reobserved at the same wavelength with the same grating, relative fluxes can be compared to 1% or better. (PSF has sharp peak, so sensitivity to centering is greatly reduced.)
- If the same star is observed, but at different wavelengths, then modest systematic effects enter, and limit is 3 to 4% in worst case, 2% typically. Worst case arises from shape effects mentioned above, and is an upper limit.

- All of the above are for LSA observations. SSA fluxes need to include effects over an orbit, which can be as much as 10% as a relative effect and more than that if initial centering in SSA was poor.

2.8. Wavelength Calibrations

Aperture offsets This is the apparent shift in wavelength between light from different apertures due to different angles for entering light. The convention is to refer all GHRs wavelengths to SSA. The post-COSTAR offsets reported in ISR080.

Doppler compensation The onboard doppler compensation moved spectra on the photocathode to oppose the motions induced by orbital speed of spacecraft. Some early observations had wrong compensation applied, leading to significant errors. This was fixed in April, 1993. Moving target observations before July, 1994, are incorrect. Observers were notified at time error detected. ARs should use `obsum` task to check for this.

Using wavecals and SPYBALs The wavelength calibration program shows that the default wavelength scale (dispersion) is highly reliable and needs no correction. Default zero point can be off by 60 mÅ (typical, for medium-resolution gratings), as determined from wavecals. A SPYBAL can correct to 19 mÅ or better (ISR053). (A SPYBAL is a SPectrum Y BALance exposure taken with same grating as science observation but at a standard wavelength.)

2.9. Spatial Uncertainty and Target Acquisition

Acquisitions ISR079 discusses GHRs target acquisitions and problems encountered and has been incorporated into the latest DH. Paper products provide a graphical check on pointing (jitter ball).

Acquisitions in early years could not use `BRIGHT=RETURN` and needed explicit `BRIGHT` and `FAINT` limits. This led to some acquisition problems that are documented.

Line Spread Functions (LSFs) These are documented in ISR063.

The Far Wings of the PSF See ISR083.

2.10. Timing Uncertainty

The actual times of observations are not recorded, and must be inferred from when the observation ended.

Exposure start time The packet time (`PKTTIME`) of first group in UDL is the closest estimate to start time of observations, except for RAPIDs. The UDL was always created prior to start of exposure, and `PKTTIME` is good to within 1/8 sec. For RAPIDs, `PKTTIME` in calibrated science headers represents when data left GHRs.

Exposure end time For ACCUMs, another UDL was generated at the end of observations, so use the `PKTTIME` in second group of UDL. For multiple readouts (e.g., FP-SPLITS), UDLs come in pairs that bracket the science. For RAPIDs, the second UDL was not dumped until the end of the observing sequence.

Exposure duration This is in `EXPTIME` keyword. Exposure per pixel is calculated for reduced data.

Interruptions GHRs was HST's only interruptible instrument, making scheduling flexible, although limiting in some ways. Precise interrupt information is not possible to determine except with detailed examination of OMS data.

2.11. Instrument and Spacecraft Errors

Carrousel resets This was a frequent problem that increased over life of instrument. Some flight software changes were made to mitigate the effects of resets, especially for acquisitions. Resets could lead to early termination of ACCUMs; this is revealed through FINCODE in header since about 1995.

Data transmission errors Reed-Solomon checking is used for data transmission. If an error is detected, it goes into the data quality file as quality value = 1. Data losses and other situations can lead to fill data with quality value = 16.

3. GHRs Documentation

3.1. Primary document for archival researchers (ARs)

All ARs will need to refer to:

Data Handbook (DH97): It is fully up-to-date as of October 1, 1997. It incorporates recent ISRs. It is available as paper or on-line. It will be issued as part of volume 2 of DH97 in January.

3.2. Other documents

These are described and enumerated in ISR090. They are important in certain circumstances during program preparation, but should be only rarely needed by ARs.

Instrument Handbook v6 (IH6):

- Proposer-oriented description of instrument design and operation.
- Useful for understanding structure and strategy of Phase II proposals.
- Explains operating modes and options.
- Available on-line (as is IH5).
- Essential portions for ARs incorporated into DH.

Instrument Science Reports

- Primary content has been distilled into DH97.
- Some ARs may wish to read full text.
- Most ISRs since SMOV available on-line.

Earlier Instrument Handbooks: These may sometimes be needed to understand observations obtained in a particular mode or time. They will be maintained to record state of instrument at the time they were written in case that cannot be reconstructed from other documents.

Ball Technical Documents Should not be needed by ARs.

- Science Verification Report (9202)
- Ball System Engineering Reports (SERs; 134 plus 10 during SMOV; 9011 to 9404)
- SE-01 ("SI System Description...") (8510)
- Pre-Launch Calibration Report (8603)
- HRS Intermediate Calibration Report (8401)
- Orbital Verification Test Report (9205)
- Orbital Verification Data Analysis Plan (9005)
- A&V Thermal Vacuum Test Report (8611)

Related documents:

- Phase II Proposal Instructions
- TRANS Scripting Guide
- A User's Guide to the GHRs Software (IDT at GSFC)

A set of archival documentation is being saved at STScI.

4. Program Status

Calibration program: The calibration program has been reported in Calibration Plans and ISRs.

- Formal close-out exist for Cycles 4, 5, and 6.
- Plans for Cycles 3 through 6 are in ISRs.

Unanalyzed calibrations:

- Echelle wavelength monitors:
 - First-order gratings showed no problems.
 - Previous echelle analyses showed no problems (ISR058).
- Echelle-B sensitivity being checked.

Documentation close-out:

- Available documentation has been evaluated.
- Copies of paper-only documents to go to library; these have been set aside.

5. A Few Last Words...

...from the last Instrument Scientist for the GHRIS during the last week of a GHRIS Group at STScI on the last day of this calibration workshop, to the many who will not be the last users of GHRIS data.

The GHRIS was a well-designed and well-constructed instrument that showed its productivity by the time observers that requested – typically about 25% of HST time in Cycles 4 to 6, second only to WFPC2. The quality of the observations will be further shown through use of the archive.

Productivity is also shown by the record of publications that were based on GHRIS observations. Those known to us that appeared in refereed journals are:

1992: 6

1993: 21

1994: 34

1995: 54

1996: 45

1997+: 55+

These numbers are based on papers sent as preprints to the STScI library, and so are lower limits. In particular, papers in European journals are probably underrepresented.

5.1. The GHRIS Lineage:

When installed in *HST* in 2002, the HRS parts within COS will be the only remnants of the five launch instruments.

The success of the GHRIS is a credit to the many people in the Investigation Definition Team (IDT), and at Ball Aerospace, Goddard Space Flight Center, and STScI who helped to build and calibrate it.

I wish to acknowledge the contributions of all these individuals, at the risk of forgetting some. They include:

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GHRIS@ST-ECF: J. Walsh

GHRIS@STScI: J. Bacinski, W. Baggett, A. Berman, M. de la Peña, D. Duncan, J. Eisenhamer, L. Ferrarese, R. Gilliland, A. Gonnella, S. Hulbert, M. Lallo, H. Lanning, C. Leitherer, J. Mack D. Manning, M. McGrath, K. Peterson, A. Schultz, L. Sherbert, J. Skapik, D. Soderblom

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